Logistics Management Institute

Product Data Strategies for the Department of Defense

DL802T1

August 1998

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Executive Summary

The Department of Defense (DoD) manages the procurement, distribution, and repair of approximately 5 million items. Associated with the items are approximately 107 million sheets of engineering data. To physically preserve these data and to make them universally available, DoD has undertaken a large-scale project to convert them to electronic media.

Just because product data are stored electronically does not mean they become more useful. The choice of product data format determines the degree of usefulness. The approach taken by DoD is to scan existing drawings into electronic pictures called raster images. While this approach is acceptable for preserving past data, it is not sufficient for new or reengineered product data, and it is not compatible with modern, computer-aided engineering and manufacturing technologies. Those modern technologies store product data in a variety of formats, known collectively as vector formats.

DoD recognizes this and has formulated a long-term goal of representing its product data in a neutral vector format defined by an international standard. That standard, however, is incomplete and not yet supported by commercial mechanical engineering software. Therefore, DoD requires a near-term transition strategy for storing its product data in one or more currently available vector formats while awaiting the international standard to mature. We examined the available product data formats for mechanical and structural items, such as valves and bushings. Although our emphasis was on the data formats required by the Defense Logistics Agency for procuring spare parts, those formats are important throughout the product life cycle. Product life-cycle activities producing or requiring product data include initial design, production, assembly, testing, training, and maintenance.

Before defining the product data alternatives DoD could follow, we sought to understand the capabilities and trends in computer-aided design, engineering, and manufacturing. To this end, we conducted a market survey of seven leading software products: AutoCAD, CATIA, I-DEAS, Pro/Engineer, SmartCAM, SURFCAM, and Unigraphics. We noted their capabilities in areas such as modeling capability, modeling engine used, parametrics, tolerencing, engineering

analysis, product data management, and data exchange. Many of the packages offer robust capabilities in these areas. The associated competition is driving increased product integration and frequent enhancement. Today's industry standards, for neutral product data exchange, however, do not reliably capture all the essential data for design and manufacture. Also, the *rate* at which the commercial software is improving and adding capability relative to the standards, is not generally appreciated. For example, some relatively new but widely used features, such as parametrics and design constraints, are not yet included in the standards.

With an understanding of commercial engineering software capability, we formulate alternatives by which DoD could format its product data. The status quo is a two-dimensional raster format. Alternatively, data could be stored in two-dimensional or three-dimensional vector formats. Also, those vector formats could be proprietary (defined and owned by a company) or neutral (defined by industry standard). We also include an alternative derived from vector format based on three-dimensional, neutral, machine instructions. Each of these approaches has its economic and technical advantages.

Conceptually, three-dimensional, neutral, vector format is the most useful and desirable format because it contains the most complete product representation and is independent of the software used. Due to the current lack of robust standards, however, we recommend that DoD consider some combination of two-dimensional and three-dimensional proprietary formats until the standards mature. There is no single "best" format that DoD should use. The selection of a format depends on the commodity (for some products two-dimensional format is adequate, while others require three); the software in place at DoD engineering centers and their contractors; and economic considerations (frequency and dollar level of activity related to the product).

DoD does not need or collect product data for all items it buys. DoD typically does not collect product data for sole-source items and items that are to be maintained via contractor logistics support. The issue of what data to collect and in what form to collect them pertains to items that DoD intends to reprocure competitively or where the product data are needed for downstream activities, such as training or testing. For these items, we recommend that DoD take some immediate actions to capture advanced product data (including geometry, features, tolerances, and other attributes in computer-interpretable form) that its contractors are generating and to utilize the existing capability of engineering software. Contractors create these data not only during initial design but also during reprocurement, so DoD can begin collecting them on virtually any competitive item it buys.

DoD should survey its suppliers and determine what product data formats they support and should do the same with its internal engineering activities. DoD should upgrade its electronic data library (the Joint Engineering Data Management Information and Control System,) to accommodate files of any format and provide

users with the capability to view those files. DoD should form a cross-functional team to identify and resolve technical issues (e.g., software revision control) with accepting, storing, and distributing product data in several formats. Most important, DoD should recognize that no single format will suit all of its needs, and that the formats it uses will change over time as software capabilities evolve.

One approach for comprehensively addressing these recommendations would be to organize an Advanced Technology Concept Demonstration under the Defense Science and Technology Program. That demonstration could be managed by the Joint Electronic Commerce Program Office with participation of the military services and the Defense Logistics Agency.

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Chapter 1
Problem Statement

Department of Defense (DoD), through its Defense Logistics Agency (DLA), manages approximately 4 million consumable items to support military operations. The military services manage roughly an additional 1 million reparable components and end items. Associated with these 5 million items, DoD owns approximately 107 million sheet images of engineering data.[1] While most of these data were originally produced by private-sector defense manufacturers, DoD has acquired the data to competitively procure spare parts, to maintain defense hardware in the field and in depots, and to modernize weapon systems when a private contractor is not available.

Historically, these data have been recorded on paper and then photographed and attached to aperture cards. These media are undesirable because they can be physically difficult to access and reproduce, they are subject to physical damage, and they deteriorate over time. Perhaps most significantly, these media are incompatible with modern mechanical engineering software technologies.

In the late 1980s, DoD embarked on an effort to scan virtually all its product documents into electronic format. DoD has chosen an approach that converts its product data into electronic "pictures" called raster images. This approach solves the problems of physical access and damage. As such, it preserves the data representing the way products were originally designed and made. DoD's approach, however, does not address the way products are designed and made today and the ways in which they will be made in the future.

Substantial engineering software capabilities exist today, and they are evolving rapidly. Those capabilities mean that product definition data are useful to many functions, such as manufacturing and training. Each function can use the data in electronic form to visualize the product and to perform actions on the product.

DoD—from military engineers to high-level managers—is aware of the capabilities offered by engineering software, but has yet to define a structured approach to adopting those capabilities, especially with respect to spare parts procurement. In the field, at defense engineering activities and repair depots, DoD engineers do have a panoply of advanced engineering software. The problem lies not in what engineering software DoD employs, but in what format or formats it chooses to issue the resulting data to contractors for product procurement.

[1] Joint Engineering Data Management Information and Control System (JEDMICS) Home Page on the World Wide Web at http://206.3.148.4/gsc/c4spec/C4SPEC03.HTM, 8 July 1998.

The current DoD practice is to convert all product data, whether from paper or the most advanced software system, into the lowest electronic common denominator—raster format. This practice means that contractors taking advantage of computer-aided engineering and manufacturing systems must take DoD's raster data and recreate the data in more advanced formats. While DoD is nominally paying for the manufacture of parts, it is in reality paying for data format conversion, engineering validation, and manufacturing. DoD takes delivery of the resulting parts but does not take delivery of the "intelligent" data that helped to produce those parts. If, for competitive items, DoD makes future awards to different contractors, it pays for the data reengineering again and again.

DoD does recognize the advantages of more advanced formats, generally referred to as vector formats. For the time being, however, DoD is awaiting the completion and industry adoption of a series of international standards known collectively as ISO 10303, *Industrial Automation Systems and Integration—Product Data Representation and Exchange* (STEP). While other vector formats (some proprietary and some open) are readily available today, DoD is taking a wait-and-see position, hoping for the complete development and acceptance of STEP.

ISSUES

The thoughts presented in this paper began when DLA asked the Logistics Management Institute (LMI) to investigate the economics associated with preparing STEP-formatted files. As background to that investigation, we formulated the following questions:

- What is the status of STEP?
- What are the capabilities of STEP relative to commercially available mechanical engineering software products?
- What alternatives to STEP, if any, exist?

In the remainder of this paper, we examine the state-of-the-art in commercially available design and manufacturing software (with some examination of engineering analysis capability also). In parallel, we examine the capability of STEP and another leading standard to incorporate the software products' data. We then develop five product data format strategies that DoD could adopt: the present strategy plus four alternatives that would capture and utilize data in advanced software formats. We emphasize that the alternatives are *not* mutually exclusive; each approach might be appropriate for a different set of circumstances and, thus, DoD could adopt all simultaneously. We end the paper with our findings, conclusions, and recommendations for developing the strategies more fully and implementing them.

SCOPE

We focus on strategies and software supporting the design and manufacture of mechanical and structural items, such as aircraft, automotive, and ship components. While strategies for electronics and other commodities are also important, we focus on mechanical items for several reasons. First, mechanical and structural items are omnipresent. Second, their engineering represents a significant cost to DoD. Approximately 13 percent of defense industry engineers are mechanical engineers, and another 12 percent are aeronautical engineers.[2] Finally, the international standards supporting the interchange of mechanical product data are more fully developed than those for other commodities. If a standard-based strategy (such as STEP) is to be adopted by DoD, it should be first adopted for a commodity where the standard is mature.

[2] Logistics Management Institute, *The Defense Manufacturing Base: Activity-Based Cost Profiles and Their Implications for Funding Manufacturing Technology*, Report NT301R1, Eric L. Gentsch, et al., January 1994, p. D-4.

Chapter 2

Engineering Software Capability Survey

Before outlining alternative product data strategies available to the DoD, we sought to identify the major mechanical engineering software products and their capabilities. We focused on software for computer-aided design (CAD) and computer-aided manufacturing (CAM). Because the industry is evolving so rapidly, it is important to consider not only DoD's current requirements, but also what capabilities off-the-shelf products offer and what capabilities are emerging. With a view of what commercial software capabilities are, and are likely to be, DoD can make more informed decisions in establishing its requirements for procuring software and for maintaining product data.

In this section, we first present the CAD products with the largest market share. We then provide a capabilities comparison for some of the major CAD products and some of the major CAM products.

The overall CAD market is estimated at $4.7 billion, having grown 17.2 percent in 1997 and 18.5 percent in 1996. Table 2-1 lists the CAD market leaders, as defined by 1997 sales. Note that some consolidation is taking place, as Parametric Technology Corporation has acquired Computervision to complement its Pro/Engineer line, and Dassault Systemes now owns SolidWorks in addition to its long-standing CATIA product.

In the following sequence of tables, we present the results of a market research study aimed at comparing the capabilities of some major CAD/CAM products. We included some major CAM products because of the increasing integration of CAD and CAM capabilities and because of a possible strategy, discussed later in this paper, whereby DoD could receive, store, and distribute manufacturing process data. The software capabilities that we list are based on vendor's published specifications; other than prior personal experience by the authors with some of the products, we made no attempt to validate the functionality claimed by the vendors.

Table 2-1. The 1997 CAD Market Leaders

Product names	Company	1997 market (millions)
Pro/Engineer	Parametric Technology Corporation	$850
CATIA	Dassault Systemes (marketed by IBM)	$802
I-DEAS	SDRC	$320
SolidWorks	Dassault Systemes	$280
Computervision	Parametric Technology Corporation	$240
AutoCAD	Autodesk	$230
Unigraphics and SolidEdge	Unigraphics Solutions (EDS)	$220
MICROCADAM	CADAM Systems Company	$200
MSC/Patran, MSC/Nastran, and SuperForge	MacNeal-Schwendler Corporation	$170
SolidDesigner	CoCreate (Hewlett Packard)	$160
EUCLID, STRIM, and Prelude	Matra Datavision	$155
MicroStation, EMS, and SolidEdge	Intergraph	$110

Note: SolidEdge is a joint venture between Unigraphics Solutions and Integraph.

Source: "CAD/CAM Sales Skyrocket," *Computer-Aided Engineering,* January 1998, p. 14.

Table 2-2 lists the CAD/CAM products whose capabilities we surveyed. We include two neutral file formats: ANSI/US PRO/IPO 100-1996, *Initial Graphics Exchange Specification IGES 5.3* (IGES), and the ISO 10303 series titled *Industrial Automation Systems and Integration—Product Data Representation and Exchange* (STEP). As neutral formats, they offer the potential to translate data from any system to any other system; we wanted to see what systems indeed support those formats. Also, the translation of data involves both quantity (translating all available data types) and quality (translating each data type correctly). We wanted to see what features or capabilities offered by the CAD/CAM products that the neutral formats could handle. Any data type not handled by the neutral formats will be lost in translation.

Table 2-2. Overall Capabilities of Major CAD/CAM Systems

System	Company	Operating system	Capability
AutoCAD Mechanical Desktop 2.0	AutoDesk www.autodesk.com	Windows 95 Windows NT	CAD
CATIA	Dassualt Systemes/IBM www.catia.com	AIX UNIX	CAD/CAM/CAE
I-DEAS Master Series 6	SDRC www.sdrc.com	Unix Windows NT	CAD/CAE
Pro/Engineer	Parametric Technology Corporation www.ptc.com	Unix Windows NT	CAD/CAM/CAE
SURFCAM 7.0	Surfware www.surfware.com	Windows 95 Windows NT	CAM
Unigraphics	EDS www.unigraphics.com	Unix Windows NT	CAD/CAM/CAE
IGES	None—industry standard	Not applicable	File format only
STEP	None—industry standard	Not applicable	File format only

Note: CAE = computer-aided engineering.

In Table 2-3, we display the basic modeling capabilities of the products. Modeling refers to the software's capability to generate geometry.

Table 2-4 shows some general modeling features of the products. The modeling engine refers to the underlying software that generates and represents the geometry of the product. Different software products using the same modeling engine can generally read and manipulate product geometry without data loss. In some respects, third-party modeling engines, such as ACIS and Parasolid, can be viewed as *de facto* standards that will compete with the formal standards IGES and STEP for market acceptance.

Neither the IGES nor the STEP standards support parametric design and "tolerancing." Tolerancing is the ability to specify manufacturing limits about nominal design dimensions. Parametric design and the ability to include design constraints are widely available capabilities that the standards bodies have been slow to adopt. Tolerencing is anticipated to emerge in STEP's AP 224, but it is not yet supported by the software industry. Note also that the modeling engines ACIS and Parasolid do not support these features either; where offered (e.g., in AutoCAD), parametrics and tolerancing data are "extra" to the data stored by the modeling engine.

Table 2-3. Modeling Capabilities of Major CAD/CAM Products

System	2-D Vector	3-D Surface	3-D Solid
AutoCAD Mechanical Desktop 2.0	Yes	Yes: NURBS and splines	Yes: CSG and feature-based
CATIA	Yes: includes 2-D/3-D integration	Yes: polynomials, splines, Bezier, and-NURBS	Yes: CSG
I-DEAS Master Series 6	Yes	Yes: NURBS, Bezier, lofted surfaces, ruled surfaces, and surfaces of revolution	Yes
Pro/Engineer	Yes	Yes: NURBS, Bezier, and polylines	Yes: CSG
SmartCAM	Yes	Yes: NURBS and polylines	Yes: CSG
SURFCAM 7.0	Yes	Yes: NURBS, Bezier, and polynomials	Yes: B-Rep (uses SolidWorks Modeler)
Unigraphics	Yes	Yes: Lofted surfaces and surfaces of revolution	Yes: CSG
IGES	Yes	Yes: NURBS, splines, Bezier, and polynomials	No
STEP	Yes: AP201 (but no industry translators available)	Yes: AP203 Future: AP214 (manifold surfaces)	Yes: AP203 (B-Rep) Future: AP214 (B-Rep, CSG, others) and AP224

Notes: AP = application protocol; CSG = constructive solid geometry; NURBS = non-uniform rational b-splines; B-Rep = boundary representation.

Constructive solid geometry represents solid objects as unions, intersections, or differences of other solid objects.

Table 2-4. Modeling Features of Major CAD/CAM Products

System	Modeling engine	Parametric	Tolerancing
AutoCAD Mechanical Desktop 2.0	ACIS 3.0	Yes	Yes
CATIA	Proprietary	Yes	Yes
I-DEAS Master Series 6	Proprietary	Variational with graphical display of constraints	Yes
Pro/Engineer	Proprietary	Yes	Yes
SmartCAM	ACIS 2.1 and Proprietary	No	Yes: dimensioning and notes
SURFCAM 7.0	Parasolid and Proprietary	Yes	Yes: tolerant modeling
Unigraphics	Parasolid	Variational with constraints	Yes
IGES	Not applicable	No	No
STEP	Not applicable	No	Future: AP214, AP224

Notes: The ACIS modeling engine is a product of Spatial Technology Corporation. The Parasolid modeling engine is a product of Unigraphics Solutions (an EDS company).

Table 2-5 shows the design, engineering analyses, and product data management tools that are supported by the CAD/CAM products. "Design tools" refers to capabilities specific to various commodities, such as sheet metal and molding. Engineering analyses refers to capabilities for performing static, dynamic, thermal, or other evaluations of a design. Product data management is the process of storing and accessing data supporting the design, such as bills of materials and configuration management.

Table 2-5. Design, Analysis, and Data Management Capabilities of Major CAD/CAM Products

System	Design tools	Engineering analyses tools	Product data management
AutoCAD Mechanical Desktop 2.0	Yes: through third-party software	Yes: part properties and other capabilities through third-party software	Yes: through third-party software
CATIA	Yes: sheet metal, composites, molds, and dies	Yes: part properties, kinetic analysis of assemblies, and finite element analysis	Yes: bill of materials and revision control, access control, searchable database, and part library
I-DEAS Master Series 6	Yes: molds and dies, hulls, injection molding, sheet metal, wiring harnesses, and material data catalogs	Yes: part properties; part comparison; nonlinear finite element analysis (acoustic, modal, structural, fatigue); and dynamic analysis	Yes: manages all part, assembly, drawing, engineering analysis, test, and machine data within team project environments
Pro/Engineer	Yes: optimization	Yes: part properties, stress, thermal, stiffness, vibration, and impact	Yes: integrates part data with manufacturing, marketing, and management data; controlled access; and relational database for searching
SmartCAM	No	No	No
SURFCAM 7.0	Yes: molds and dies and plastic parts	No	No
Unigraphics	Yes: injection molding, sheet metal, connection to ICAD* for knowledge-based engineering, wiring harnesses, and routing	Yes: injection molding and finite element analysis	Yes: bill of materials management, part revision, manages design team access, relational database can allow search on product attributes
IGES	Not applicable	Not applicable	No
STEP	Not applicable	Not applicable	Future: Some capability to store product data in AP224; AP232

*ICAD is sold by Knowledge Technologies International under license from Concentra.

Table 2-6 lists the manufacturing assembly tools offered by the CAD/CAM products. Manufacturing tools support the creation of process plans, such as routings, tool and fixture lists, and machine instructions. Assembly tool capabilities include checking for clearance and tolerance overlap.

Table 2-6. Manufacturing and Assembly Tools Offered by Major CAD/CAM Products

System	Manufacturing tools	Assembly tools
AutoCAD Mechanical Desktop 2.0	Yes: through third-party software	Yes
CATIA	Yes: process planning; NC programming (2- to 5-axis milling and turning); tool libraries; NC code analysis; tool path verification; sterolithography; and robotic programming	Yes: automatic functional dimensioning and toleranacing
I-DEAS Master Series 6	Yes: integrated with CAMAX and SmartCAM, SDRC's NC programming systems	Yes: standard parts catalog
Pro/Engineer	Yes: material libraries; tool libraries; fixture libraries; cutting database; NC programming (2.5-to 5-axis milling, 2- to 4-axis turning, 2-axis electro discharge machining)	Yes: kinematic analysis including cams, slots, and gears
SmartCAM	Yes: material libraries, tool libraries; NC programming (2.5- to 5-axis milling, 2-to 6-axis turning, 2- to 5-axis electro discharge machining, punch and waterjet); tool path verification; part nesting; and tool path optimization	No
SURFCAM 7.0	Yes: tool libraries, fixture libraries, 2-to 5-axis NC milling and turning, and tool path verification through integration of third-party software (SIRIUS)	No
Unigraphics	Yes: NC programming (2- to 5-axis milling, 2-axis turning, 2-to 5-axis electro-discharge machining, tool path verification through third-party software, tool inventory management, machining database, sheet metal fabrication, and sheet metal nesting	Yes: standard parts catalog, kinematic with library of machine elements, and component clearance analysis
IGES	Not applicable	Not applicable
STEP	Not applicable	Not applicable

As shown in Table 2-7, all of the products we examined support the IGES interchange standard. Most support the STEP AP203, which translates nominal geometry. None of the products support STEP's two-dimensional standard, or the anticipated AP224 that includes manufacturing data. Increasingly, CAD vendors are offering direct translators (e.g., I-DEAS to AutoCAD) that are tuned to the specific packages. In addition to these exchange formats, which enable the data to be edited, almost all CAD vendors now offer software that enables files in their native format to be viewed (including pan, zoom, and rotation), but not edited. Much of this software can be downloaded from the Internet for free or for a nominal charge.

Table 2-7. Data Exchange Formats Offered by Major CAD/CAM Products

System	Data exchange formats
AutoCAD Mechanical Desktop 2.0	IGES Version 5.3, STEP AP203, DWF, DWG, DXF, IDF, SAT (ACIS), STL, VRML, and 3DS (3-D Studio)
CATIA	IGES Version 5.2, STEP AP203 and 214, CATIA-CADAM, CATIA-ALIAS, CALS, DXF, DWF, and Hybrid Raster
I-DEAS Master Series 6	IGES 5.3 with tuned translators for major CAD systems, STEP AP203 and 214, ABAQUS (to/from), ANSYS (to/from), AutoCAD (to/from), CADAM (to/from), CADDS 5 (to/from), CAMAND (to), CATIA (to/from), JAMA-IS, NASTRAN (to/from), Pro/Engineer (to), SmartCAM (to), and Unigraphics (to/from)
Pro/Engineer	IGES, STEP AP203 and 214, CADAM, CADDS 5, CATIA, I-DEAS, PDGE (Ford), and STL
SmartCAM	IGES, SAT (ACIS), DXF, and DWG
SURFCAM 7.0	IGES with tuned translators for major CAD systems, CADL, SAT (ACIS), and DXF
Unigraphics	IGES, STEP AP203 and 214, CATIA (to/from), DXF, JAMA-IS, STL, and XT
IGES	Not applicable (IGES is a data exchange format)
STEP	Not applicable (STEP is a data exchange format)

Chapter 3
Product Data Alternatives

In this chapter, we discuss five major product data alternatives available to DoD. We label each alternative based on the underlying format in which the product data would be stored and distributed: two-dimensional raster format; two-dimensional vector format; three-dimensional, proprietary, vector format; three-dimensional, neutral, vector format; and three-dimensional, neutral, machine instructions. For each alternative, we discuss the operational scenario, economic issues, and technical issues. We also summarize JEDMICS under the first alternative because almost all of the files in that system are in raster format.

Two-Dimensional Raster Format

Product data in two-dimensional raster format are a picture of a traditional blueprint or aperture card image. Also called bitmaps, these data only can be edited by manipulating individual pixels in the image. They contain none of the object-oriented "intelligence," such as lines, surfaces, or holes, that make up more advanced data formats.

Operational Scenario

Under this alternative (which is, in fact, the standard approach today), DoD acquires product data from the initial designer and from those data (regardless of format) generates and archives a two-dimensional raster image. When the need to procure arises, the DoD buying agency would retrieve and distribute the image either as an electronic or printed "request for quotation."

To generate a quote, the contractor would perform the following tasks:

- Generate a bill of materials.
- Generate a routing for manufacturing operations.
- Identify tools and fixtures.
- From the raster image, generate computer-based geometry (e.g., a vector model) using CAD software.

- Using CAD manufacturing software, create a cutting tool path(s) from the computer model to determine machining time.

- Develop the quotation.[1]

Some contractors may develop quotations using parametric equations or rules of thumb, in which case, some of the tasks outlined above would unfold after an award is granted. Also, some or all of the tasks above might not be necessary if the contractor had built the part before and had saved the information from the earlier contract, or if a person could interpret the raster picture and use machine tools directly to make the part. Using raster-to-vector software can assist in creating vector models from raster images.[2] Following award of a contract or delivery order, the contractor would

- order raw materials and components, if necessary;
- acquire or design and build tooling and fixtures;
- complete process planning, including specification of tooling, fixturing, and tool paths;
- generate a numerical control code (machine tool instructions);
- postprocess a numerical control code;
- generate a shop floor information package, including routing information, tooling sheet(s), setup fixture sheet(s), and directions for accessing the control code for each machine;
- schedule the job; and
- make the parts.

JEDMICS

Today, DoD stores product data on paper, on aperture cards, and in JEDMICS. JEDMICS electronically stores product information previously recorded on paper and aperture cards. JEDMICS takes engineering drawings and related text that

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[1]The quotation for a batch of machined parts is usually based on a variation of the following formula: (material cost + material markup) + (setup rate × setup time) + {machine rate × (load time + cycle time + unload time) × number of parts}. The material markup covers purchasing and handling costs; the setup and machining rates include factors for overhead and profit. The first time a part is quoted, nonrecurring expenses may be added for special tooling, fixtures, and engineering time. Current machine and setup rates for precision machine shops are $50 to $60 per hour.

[2] DoD is conducting a research program, called the Automated Document Conversion System, to explore the utility of raster-to-vector conversion software and service bureaus and to fund the creation of two-dimensional vector data.

have been scanned and stores them on wide-area, network-accessible optical media, providing near-immediate online access at distributed workstations.[3]

The JEDMICS program office states that its system is the largest electronic document management system in the world, and it is growing as more documents are converted from paper and aperture cards. Table 3-1 shows the number of files in JEDMICS in March 1997. The total of approximately 40 million includes duplicates of the same image that are stored at separate JEDMICS locations. By November 1997 (the latest figure available), the system had grown to over 64 million files.

Table 3-1. Number of JEDMICS Files by Defense Component, as of 1 March 1997

Defense component	Number of JEDMICS files
Navy	25,537,391
Defense Logistics Agency	5,942,766
Army	4,280,099
Air Force	3,434,117
Total	39,194,373

Source: World Wide Web site at http://206.3.148.4/gsc/c4spec/c4spec07.htm, 11 June 1998.

While JEDMICS is nominally a library system, independent of the format of the data files stored within, JEDMICS is, in practice, synonymous with the two-dimensional raster-format images stored in it. Today, virtually all JEDMICS files are in this format, known as "C4." DoD defines the format requirements for C4 in military specification MIL-PRF-28002C, *Raster Graphics Representation in Binary Format, Requirements for*. The C4 format is a tiled, binary bitmap with a resolution of 200 pixels per inch. Using this format, JEDMICS can store images of engineering drawing sheets from ANSI A size (11 inches wide by 8.5 inches high) to ISO A0 × 3 size (2,523 millimeters wide by 1,189 millimeters high).

JEDMICS is a large advance over both paper and aperture cards for several reasons. First, it physically preserves the product information from deterioration.[4] Second, it enhances the retrieval and distribution of the data by enabling images to be transferred from a central library to remote users over a computer network. Finally, it replaces individual military service library systems and thereby offers a standard DoD format and interface.

[3] Information in this section drawn from the JEDMICS' program World Wide Web site at http://206.3.148.4/jedmics.html, 11 June 1998.

[4] Electronic storage eliminates deterioration due to handling. Optical disks do have limited lifespans, and data stored on them may need to be re-recorded every 10 years or so.

Despite these advantages, the JEDMICS C4 format has several drawbacks. Two are technical; one is philosophical. The 200 pixel per inch specification produces drawings of fair quality; some drawings need a higher degree of resolution.[5] Also, C4 data are "digital" in that they are stored on opto-electronic media and are viewed on computers, but they are "unintelligent" in that they are raster images (pictures). As such, they must be reentered into CAD systems if the product data are to be used in automated manufacturing.

This technical drawback leads to a philosophical drawback. Although JEDMICS nominally can accept files in any format, the JEDMICS operational philosophy seems to be to convert CAD files, and not just paper and aperture cards, into C4 format. For example, the JEDMICs program office, on its Web site, cites the need for software converters to translate drawings produced by CAD programs into C4 format. While a neutral format for viewing product data is desirable, by actually converting the data to C4, DoD is losing "intelligence" that the CAD systems embed in their files. Note that this drawback applies to data that DoD acquires for new products and also to data created by manufacturers when DoD reacquires existing products.

Economic Issues

While no more information exists in a raster product data file than a blueprint, raster files do have the capability of being electronically distributed (e.g., over the Internet), reducing distribution time and cost.[6] No change is likely in manufacturers' prices because they must perform the tasks with raster images as if they had received paper (a minor exception being the time saved if raster-to-vector conversion software is used). DoD might see lower data maintenance costs due to reduced storage space requirements and due to the better accounting of costs that comes with concentrating a large amount of information in a relatively few locations.

Technical Issues

Two-dimensional raster images produce technical benefits for DoD in facilitating document storage and distribution. They produce few benefits for manufacturers, who will probably need to print paper copies for their machinists and may need to produce vector-based files for their computer-based machine controls.

Raster images must be readable to be useful. The pixel resolution must be high enough to preserve the legibility of handwriting. Smudges, tears, or other defects

[5] The JEDMICS program office states that "the defense community needs image resolutions up to 1,200 pixels per inch." See the World Wide Web site at http://206.3.148.4/gsc/c4spec/C4SPEC03.HTM.

[6] Blueprints can be transmitted electronically by facsimile, but the utility of this generally is limited by paper size restrictions.

in the original document will be perpetuated after scanning into electronic format. Cosmetic defects, if not corrected, will lead to time delays during later procurements as the buyer and manufacturer will need to resolve the drawing defects. Cosmetic defects can translate to product defects if they are not apparent to a manufacturer. For example, a smudge that obliterates a key tolerance might not be noticed as a drawing defect by the manufacturer.

Two-Dimensional Vector Format

Two-dimensional vector format data resemble conventional blueprints when viewed and printed, but they contain more information and are more easily edited. Rather than being a collection of dots, a line, for example, is represented as an object connecting two points or as an object with a beginning point, direction, and magnitude (i.e., a vector). Objects, such as lines, may be copied, moved, changed, or deleted as complete entities. Objects may be grouped to represent higher order objects. Objects also can have associated properties that are stored in an object database. Most CAD packages include standard properties, such as associative dimensions and tolerances. Some CAD packages allow custom properties, where the designer can specify fields such as material, price, and color.

Many two-dimensional vector format CAD packages offer drawing layers that simplify drafting and viewing. For example, a basic drawing could be placed in one layer, and dimensions and call-outs placed in another layer.

Operational Scenario

The operational scenario for using two-dimensional vector format data is similar to that of two-dimensional raster data. Rather than acquiring or creating a raster image, DoD would acquire and store the product data in vector format. If DoD standardized on a format, the original file might need to be converted to that standard format (and verified for accuracy).

Contractors would use almost the same steps as with raster data to develop quotations, perform manufacturing engineering, and produce. Rather than creating computer models from scratch, however, contractors may be able to use the vector file as input, reducing some of the labor required for model generation.

Economic Issues

Contrasting with two-dimensional raster files, the two-dimensional vector format offers the opportunity for the vendor to use more (and re-enter less) of the government's technical data. This, in turn, could reduce prices, shorten lead-times, and improve quality.

Depending on the vector format chosen, manufacturers will incur expenses in maintaining vector-format software capability. In many cases, however, this capability is a nominal expense for two-dimensional formats and may be incurred already as a cost of business (i.e., is not incremental to DoD business).

Storing and maintaining data in vector format may require DoD to purchase software and labor to convert files into a standard format or from old software versions to new versions. Validating the vector-format file may introduce liability issues if DoD pays a contractor to do the work.

Technical Issues

The main technical benefits of two-dimensional vector data are that they are editable and, at least in terms of format, unambiguous. When manufacturers use a customer-supplied data format, fewer errors are introduced in data transcription.

If DoD chooses this strategy, it will need to decide which specific format or formats it will accept and how it will store and maintain them. DoD could accept all formats and store them in the order received. Or, it could accept all formats and convert them to a DoD standard format. Alternatively, it could require delivery of product data in a standard format. As software evolves, DoD also will require a strategy for updating files to the current software revision or for maintaining the capability to read old formats.

The wide variety of CAD and manufacturing software with proprietary modeling engines may make a neutral file format desirable to facilitate distribution from a customer to a large base of potential suppliers. Several *de facto* interchange standards are available for two-dimensional raster data, such as the DXF standard developed by AutoDesk, Inc. In addition, increasing acceptance of modeling kernels, such as those developed by Spatial Technology (named ACIS) and Unigraphics (named Parasolid) may facilitate two-dimensional and three-dimensional translation. To our knowledge, however, no CAD software offers a translator for the two-dimensional STEP format, even though it is defined by international standard.

In practice, few translators are completely accurate for all products; they require validation and cleanup after translation. Similarly, validation and cleanup may be required when upgrading a file between revisions of a single vendor's software. CAD software features frequently change, and new software versions are not always completely backward-compatible.

Compared to raster format, two-dimensional vector format adds some intelligence, but little value to product data. Two-dimensional geometry that is easily edited is of limited suitability for CAM applications. Two-dimensional geometry is sufficient for parts that are essentially two-dimensional (e.g., flat sheet metal) or

are symmetric in the third dimension (e.g., tubes), but parts with three-dimensional features generally must be entered into three-dimensional format before generating machine instructions.

THREE-DIMENSIONAL, PROPRIETARY, VECTOR FORMAT

Three-dimensional vector formats extend the idea of two-dimensional formats. They can create wire-frame, surface, and solid models. Models are collections of three-dimensional object representations, such as blocks, cylinders, slots, holes, and lofted shapes. By choosing plan, elevation, and side views, many CAD packages can create traditional-looking two-dimensional images from these three-dimensional models. The resulting data are more useable by other functions, such as simulation-based design and manufacturing using numerical-control machine tools. Three-dimensional models in proprietary format use a file structure that is specific to the CAD software vendor and that, in general, cannot be read directly by other CAD programs.

Operational Scenario

Under the strategy described, DoD would acquire product data from the initial designer and store them in a three-dimensional, proprietary, vector format. DoD could standardize on a format and require delivery in that format, or it could standardize and convert the data itself if necessary. Alternatively, DoD could support several proprietary formats and store the data in the format in which they were developed. When the need to procure arises, the DoD buying agency would retrieve and distribute the data as electronic file attachments to the request for quotation. Here, too, DoD could distribute the data as-stored or convert them to a format requested by the contractor.

To generate a quote, the contractor would perform the following tasks:

- Generate a bill of materials.
- Generate a routing for manufacturing operations.
- Identify tools and fixtures.
- If necessary, convert the product data file to the contractor's CAM software format and verify, correct, or regenerate model geometry.
- Using CAM software, create a cutting tool path from the DoD-provided computer model.
- Develop the quotation.

Note that the need to generate a computer model is eliminated because that model would be provided by DoD as part of the request for quotation package. As with the prior strategies, some contractors may develop quotations using parametric equations or rules of thumb, in which case, some of the tasks above would take place after award. Also, some or all of the above tasks might not be necessary if the contractor previously had built the part and had saved the information from the earlier contract. Following award of a contract or delivery order, the contractor would

- acquire or design and build tooling and fixtures,
- generate numerical control code (machine-tool instructions),
- postprocess numerical control code,
- schedule the job, and
- make the parts.

These last steps are unchanged from the earlier strategies.

Economic Issues

Providing contractors three-dimensional product data would reduce the time and effort required to generate process plans and machine instructions. The greater amount of data contained in three-dimensional models improves vendors' ability to produce the proper part. Also, in some cases, it is less costly to develop three-dimensional geometry using constructive solid geometry techniques than to develop two-dimensional geometry.

This strategy has, however, several economic disadvantages. Three-dimensional systems generally are more expensive to acquire (software) and require more powerful computers (hardware) than two-dimensional systems. Three-dimensional product data may also consume more storage space than two-dimensional data and may require more initial training.

One perception among government officials is that small manufacturing businesses cannot afford and are not technically savvy enough to operate advanced mechanical engineering software. While we have not performed a systematic survey, our experience indicates that many small businesses are using this software successfully. However, choosing a single proprietary format may impose a burden on some contractors and, at the same time, exclude others.

Technical Issues

Three-dimensional product modeling represents the state-of-the-art in mechanical design. Graphic visualization improves process planning, computer numerical control programming, and quality assurance. Unambiguous solid representation is necessary for semi automated and automated computer-aided process planning systems. Also, with some CAD user interfaces, it is easier to generate a three-dimensional solid than multiple two-dimensional views.

Using three-dimensional data would enable DoD to take advantage of numerous robust software systems that are commercially available. From a data quality standpoint, it is generally best to maintain a drawing in the environment in which it was developed. Also, many CAD systems are integrating analysis, kinematics, product data management, manufacturing, and assembly capabilities into their products. By providing its contractors with data already in three-dimensional format, DoD would be getting easier access to these capabilities.

The use of proprietary data formats would pose a challenge to DoD. DoD often procures products and their technical data initially from one source and later re-procures the products from another source. Dealing with a large vendor base, as DoD does, almost guarantees that it would receive data in several CAD formats. To store such data in a single format, or to translate those data to another vendor's format, would require special translators or neutral file formats.

THREE-DIMENSIONAL, NEUTRAL, VECTOR FORMAT

Product data in three-dimensional, neutral vector format are those created in a proprietary format but then stored in a standard format that can be read by any program adhering to the standard. The standard format can be *de facto*, such as the ACIS and Parasolid modeling engines, or formal, such as ANSI/US PRO/IPO 100-1996, *Initial Graphics Exchange Specification IGES 5.3* (IGES) and the ISO 10303 series entitled *Industrial Automation Systems and Integration—Product Data Representation and Exchange*.

Operational Scenario

Under this strategy, DoD would acquire product data in a three-dimensional, neutral, vector format from the initial designer and store them in that same format. If the format were truly neutral and universally available, DoD could require delivery in that format without adding materially to the original designer's effort. When the need to procure arises, the DoD buying agency would retrieve and distribute the neutral-format data as an electronic file attachment to the request for quotation.

To generate a quote, the contractor would perform the following tasks:

- Generate a bill of materials.
- Generate a routing for manufacturing operations.
- Identify tools and fixtures.
- Convert the neutral product data file to the CAM software format and verify, correct, or regenerate model geometry.
- Using CAM software, create a cutting tool path from the DoD-provided computer model.
- Develop the quotation.

Note that the need to generate a computer model is eliminated because that model would be provided by DoD as part of the Request for Quotation package. Also, the conversion to the contractor's CAM software format may be eliminated if that software supports the neutral format. As with the prior strategies, some contractors may develop quotations using parametric equations or rules of thumb, in which case, some of the tasks above would take place after award. Also, some or all of the tasks above might not be necessary if the contractor had built the part before and had saved the information from the earlier contract. The steps following a contract or delivery order award would be unchanged from the three-dimensional, proprietary, vector format strategy described above.

Economic Issues

The key advantage of the neutral file concept is that, in theory, it would enable DoD to store its product data in one format and it would allow DoD's vendors to read those data regardless of what software product they use. Data conversion errors and model reconstruction could be greatly reduced. These advantages would mean that vendors could, with less time and labor, convert DoD's product data into manufactured goods.

Given that software vendors supply translators to the neutral format, this strategy would involve no more hardware or software cost than the three-dimensional, proprietary, format strategy, because it would use the vendors' existing systems. It could even reduce costs for manufacturers who are now maintaining multiple CAD platforms.

Technical Issues

While the promise of neutral format exchange between CAD systems is very powerful, the standards defining those formats are immature and not yet fully

supported by CAD software providers. While many CAD packages support IGES, that standard does not provide for complete and accurate product representation. STEP is less mature. Only 3 of the approximately 30 application protocols defining product data within STEP have been designated international standards (the remainder are in various stages of draft and committee review). Of the main application protocols relating to the design of mechanical parts, one is an international standard: ISO 10303-203:1994, *Industrial Automation Systems and Integration—Product Data Representation and Exchange—Part 203: Application protocol: Configuration controlled design*. That standard defines nominal three-dimensional geometry. Most CAD software vendors do provide translators for AP203. This standard does not, however, contain sufficient data to manufacture a part. It lacks both tolerances and supporting text information (e.g., material specifications and process notes). The second application protocol, tentatively named *Industrial Automation Systems and Integration—Product Data Representation and Exchange—Part 224: Application Protocol: Mechanical Parts Definitions for Process Planning Using Machining Features*, promises to address these shortfalls. Unfortunately, that standard has not yet been approved and no software vendors support it yet.[7]

Even if the standards were mature and supported by the CAD industry, their advantage would not be clearcut. Computer modeling systems' capabilities are very complex and are undergoing continuous development. The introduction of new features and capabilities is central to the competitiveness of the CAD industry. Given the slow pace of STEP, it is questionable whether the development of a standard exchange protocol can keep pace. For example, STEP AP224, even if implemented, will not support parametric design, which is a recent but widely available CAD capability.

Three-Dimensional, Neutral, Machine Instructions

All of the product data strategies previously described center around the format of the product model itself. Three-dimensional, neutral, machine instructions would store the process to make the product. This strategy would require an accompanying product model, probably in a three-dimensional format. The strategy probably would be limited to mechanical parts that can be made by computer-controlled machine tools using standard fixtures and tooling. While machine tool controllers are not standardized, standards do exist for the transfer of instructions from CAM software to the machine tools. Two such standards are ANSI/EIA 274-D-1980 (R1988), *Interchangeable Variable Block Data Format for Positioning, Contouring, and Contouring/Positioning Numerically Controlled Machines* and ANSI/EIA 494-B-1992, *32-Bit Binary CL (BCL) and 7-Bit ASCII CL (ACL) Input*

[7] The South Carolina Research Authority has, under the sponsorship of DoD, developed an AP224 translator for Pro/Engineer.

Format for NCM. Instructions in these standard formats must be run through widely available "post-processors" to customize them to the input format required by the particular machine tool and controller to be used.

Operational Scenario

This strategy would transfer manufacturing engineering (i.e., process planning, the activity required to translate a design into manufacturing instructions) from a recurring activity (and cost) to a nonrecurring activity. Under this strategy, DoD would acquire product data in a three-dimensional, vector format (proprietary or neutral) from the original manufacturer. The original designer, a private-sector service bureau or DoD would perform the contractor's pre award manufacturing engineering steps listed under strategies previously described as follows:

- Generate a bill of materials.
- Generate routings for manufacturing operations.
- Identify fixtures, tooling types, sizes, speeds, and feeds.
- Create a tooling path.

In addition, the manufacturing engineering activity would create a cutter location data file in one of the standard formats listed in the introduction to this section. DoD would take delivery of the product data (i.e., CAD) file and the cutter location (i.e., CAM) file and archive those files. When the need to procure arises, the DoD buying agency would retrieve and distribute both files as electronic attachments to the request for quotation.

To generate a quotation, the contractor would review the product data file and cutter location file and estimate his costs based on material requirements and the provided process. The format of the product data file is not of particular importance to this strategy, because almost all major CAD vendors provide either free or nominal-cost software with which their models can be viewed and printed (but not edited).

Upon award, the contractor would acquire tooling and fixtures (if necessary because this approach depends on the use of standard tooling and workholding) and feed the cutter location file into post-processing software. The contractor then would need to link the tools in the machine instruction file to the specific machine tool's tooling list. If it were necessary to change the standard process, the numerical code could be easily reprogrammed. For example, the sequence of operations could be altered by simple "cutting and pasting" in the control file.

Economic Issues

This strategy appears attractive because it eliminates the issue regarding in what format to provide a product model to manufacturers. DoD could maintain product data in any three-dimensional format that it chooses because almost all proprietary formats can be inexpensively viewed by manufacturers. DoD may get reduced prices because it would only buy machine hours from vendors, having already paid for manufacturing engineering. Similarly, production lead-times might be lower because of the elimination of engineering time. However, because the "standard" process plan and machine instructions selected by DoD (or its service bureau) might not be optimal for any given manufacturer, the manufacturing portion of part prices could be higher.

Technical Issues

The technical challenges posed by this strategy are significant and have not been shown to be feasible in a regular procurement environment. First, it is likely that a computer numerical control program of any complexity will have programming errors. This could pose problems for manufacturers (and increase cost), because it is much more difficult to debug someone else's program. DoD cannot respond quickly today to manufacturer's questions on two-dimensional blueprints, and so it may not be able to respond quickly to future questions regarding machine tool instructions. The risk would be minimized, however, if DoD took delivery of a validated part along with the part data.

Second, it will be difficult to stay current with new tooling and fixturing. These factors can have a significant impact on the tool path used, on machine speeds and feeds, and ultimately on product cost. Finally, DoD would need a format and procedure by which to communicate routing, tool, and fixture plans with the machine instructions.

Chapter 4
Findings, Conclusions, and Recommendations

On the basis of our market survey of CAD/CAM capabilities and the capabilities of IGES and STEP, we summarize our findings and conclusions:

- The CAD/CAM software market offers many advanced capabilities, increasing integration among products, and is evolving rapidly due to competition.
- The mechanical engineering software industry is consolidating, making it a bit easier to identify the leading vendors. Six companies—Parametric Technology Corporation, Dassault Systemes, SDRC, AutoDesk, Unigraphics, and CADAM Systems—accounted for 70 percent of 1997 industry sales.
- DoD, by establishing standard practices built around raster format, is losing product data created by its manufacturers in CAD or is being forced to capture those data in other less efficient formats.
- Today, STEP can handle only part of DoD's product data storage needs, specifically, only nominal three-dimensional geometry. Commonly used capabilities, such as parametrics, design constraints, and product data management, are not in any near-term STEP implementation plans.
- The STEP APs, if completed and adapted by industry, would dramatically simplify DoD's tasks of storing, maintaining, and distributing data for competitively procured items.
- Commercial industry, while hopeful for STEP, is not waiting. They exchange data in proprietary formats and in IGES and use point-to-point translators. Exchanges are not perfect, but the benefits of state-of-the-art CAD outweigh the effort required to clean up transferred data.

On the basis of our findings and conclusions, we recommend these actions:

- DoD should formally recognize the immaturity of STEP and adopt interim advanced product data formats. We recommend, as appropriate to the particular commodity and product in question, the two-dimensional and three-dimensional vector approaches outlined above.

- DoD still should support the development of STEP and await its eventual widespread acceptance. As STEP APs mature, DoD should validate that they indeed store the data DoD needs and develop a transition plan away from proprietary formats.

- DoD should conduct a survey to determine what specific product data formats (i.e., CAD software packages) its current and potential suppliers use most. The survey should determine which formats the suppliers would prefer DoD to use and which they would accept if necessary.

- DoD should conduct an internal survey to determine what product data formats it is capable of creating and maintaining within military service and DLA engineering activities.

- DoD should more fully use the JEDMICS capability to store and retrieve files of any format and configure users to enable that capability. The JEDMICS capability should include the commercially available viewers for common CAD formats, and it should also consider the increasingly available Internet browser-based viewers.

- For hardware procurements in which DoD today implicitly pays contractors to produce "smart" CAD data from "dumb" raster data, DoD should take delivery of CAD data along with the hardware. This practice would apply to competitively procured items, and it would depend on DoD's ability to validate the data and store them within JEDMICs.

- DoD should form a cross-functional government and industry team to determine the most technically feasible and affordable approach for maintaining capability (both human and machine) in multiple product data formats.

- The DoD team should define how to handle CAD/CAM software upgrades and file revisions. That team should first survey how large commercial firms (for example, the commercial aircraft and automotive industries) attack the problem.

- DoD should recognize that no single format will suit all of its needs and that the formats it uses will change over time as software capabilities evolve. Economic considerations, the commodity being represented, and the state of CAD/CAM for the commodity will dictate how advanced the format is that DoD can feasibly maintain. Flexibility and the ability to adapt new formats over time will be key.

- DoD should conduct a feasibility study of the three-dimensional, neutral, machine instructions alternative.

One approach for comprehensively addressing these recommendations would be to organize an Advanced Technology Concept Demonstration under the Defense Science and Technology Program. That demonstration could be managed by the Joint Electronic Commerce Program Office with participation of the military services and the Defense Logistics Agency.

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DoD has undertaken a large-scale project to convert engineering drawings to electronic raster images. While DoD's approach is acceptable for preserving past data, it is not sufficient for new or reengineered product data, and it is not compatible with modern, computer-aided engineering and manufacturing technologies. DoD recognizes this and has formulated a long-term goal of representing its product data in a neutral format known informally as STEP. The international standard defining STEP, however, is incomplete and not yet supported by commercial mechanical engineering software. In this paper, we present a survey of current capabilities in computer-aided design and manufacturing software. We evaluate the ability of STEP to capture data created by that software. We present four alternatives, including STEP, by which DoD and its contractors could utilize more advanced product data than they do today. Finally, we develop a near-term transition strategy for capturing product data in currently-available formats while awaiting the STEP standard to mature.

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